1st MONOLITH Workshop,
15-16.Sept.2022, Geneva

Radiation induced gain layer degradation

M.Moll (CERN EP-DT)

Outline:

- **Radiation induced degradation of gain layers in LGADs**
  - LGAD gain layers
  - Carbon co-doping
- **Defect spectroscopic measurements & microscopic origin of acceptor removal**
  - (a) On dedicated test structures
  - (b) On LGAD sensors
- **Outlook:**
  - Ongoing projects to improve radiation hardness and deepen the understanding of the damage mechanism.
- **Summary & Discussion**

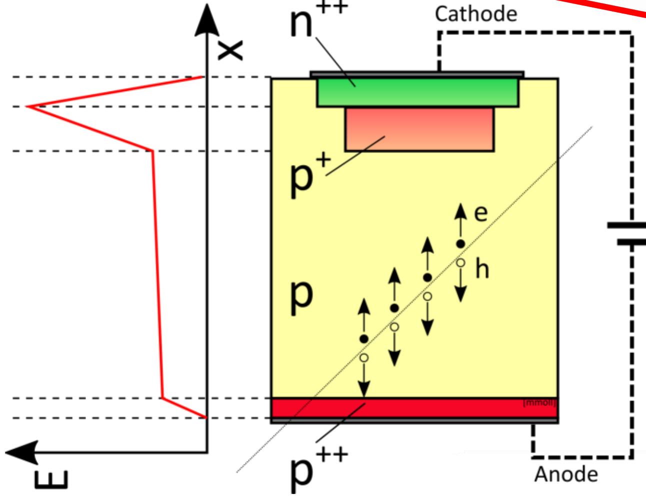
Sensors for 4D tracking
LGAD: Low Gain Avalanche Detectors

- **Origin:** Pioneered by RD50 with CNM, Barcelona and then FBK,Trento
  - RD50 working on LGADs since ≈2010 (> 60 production runs)
- **Application:** LGAD for timing detectors
  - Intrinsic gain of devices allows for excellent timing performance (<50ps)
  - Time-tagging of particle tracks in order to mitigate pile-up effects
  - Will be implemented in ETL (CMS) and HGTD (ATLAS)
- **Concept:** similar to APD but lower gain O(10), finely segmented for tracking
  - Impact ionization in p^+-implant (multiplication layer) produces gain
  - Tailored multiplication layer ([B]~10^{17}cm^{-3}); challenge: optimize gain vs. breakdown
- **Foundries:**
  - CNM (Barcelona, ES), FBK(Trento,IT), HPK (Japan), IHEP(Bijing, China), Micron(UK),
    BNL(USA), CIS(Erfurt, Germany), ….
- **Areas of LGAD developments within RD50**
  - **Timing performance**
    - Optimization: sensor thickness, gain layer profile and signal homogeneity (weighting field)
  - **Fill factor and signal homogeneity**
    - Gain layer needs protection against breakdown (JTE) causing non-efficient area
    - Mitigation: New and optimized LGAD concepts investigated
  - **Radiation Hardness**
    - Problem: Field in gain layer dropping due to “acceptor removal”
      - Defect Engineering of gain layer: Use ~~Ga instead of B~~ or C co-implantation
      - Modification of gain layer profile
  - **Performance Modelling**
    - Predictive model for operation performance (radiation, temperature, thickness, annealing, ….)

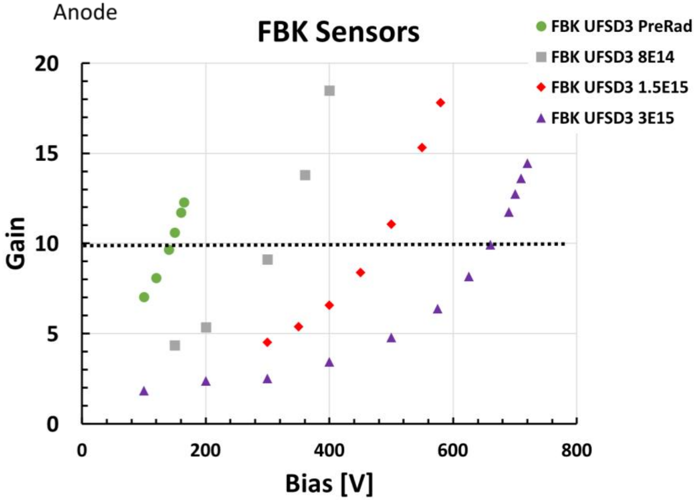
Details on LGADs see e.g:

11:25 **Overview LGAD technology at FBK**
Speaker: Giovanni Paternoster (Fondazione Bruno KEssler)

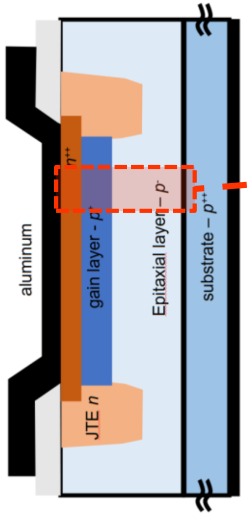
11:45 **AC−coupled LGAD with HPKK technology**
Speaker: Koji Nakamura (High Energy Accelerator Research Organization (JP))



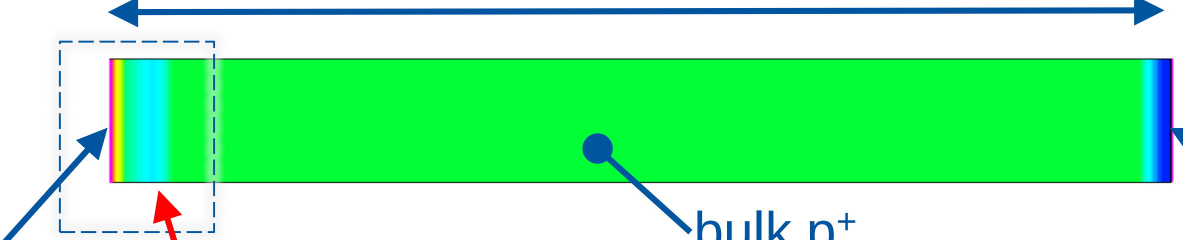
$$\sigma_{jitter}^2 = \frac{Noise}{dV/dt} \approx \frac{t_{rise}}{S/N}$$



LGAD: Deep and shallow gain layers



≈ 50µm



bulk p^+

p^{++}

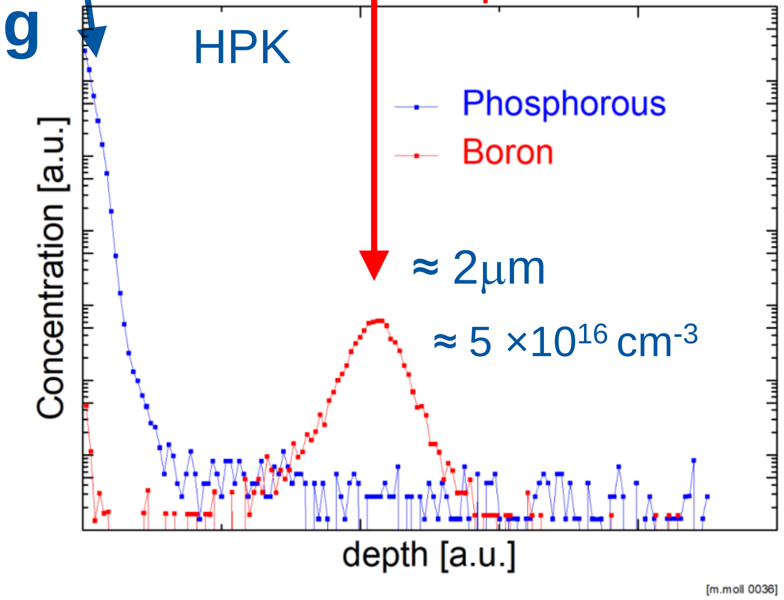
n^{++}

p^+ - gain layer

“deep”

“shallow”

log



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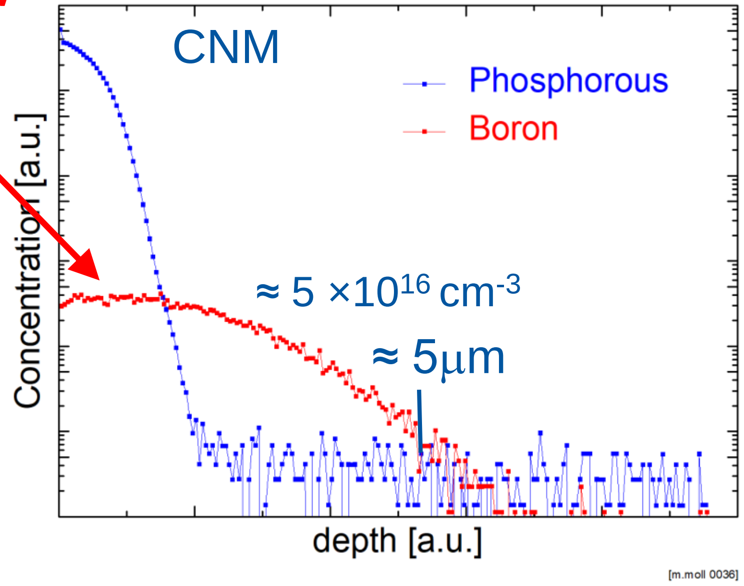
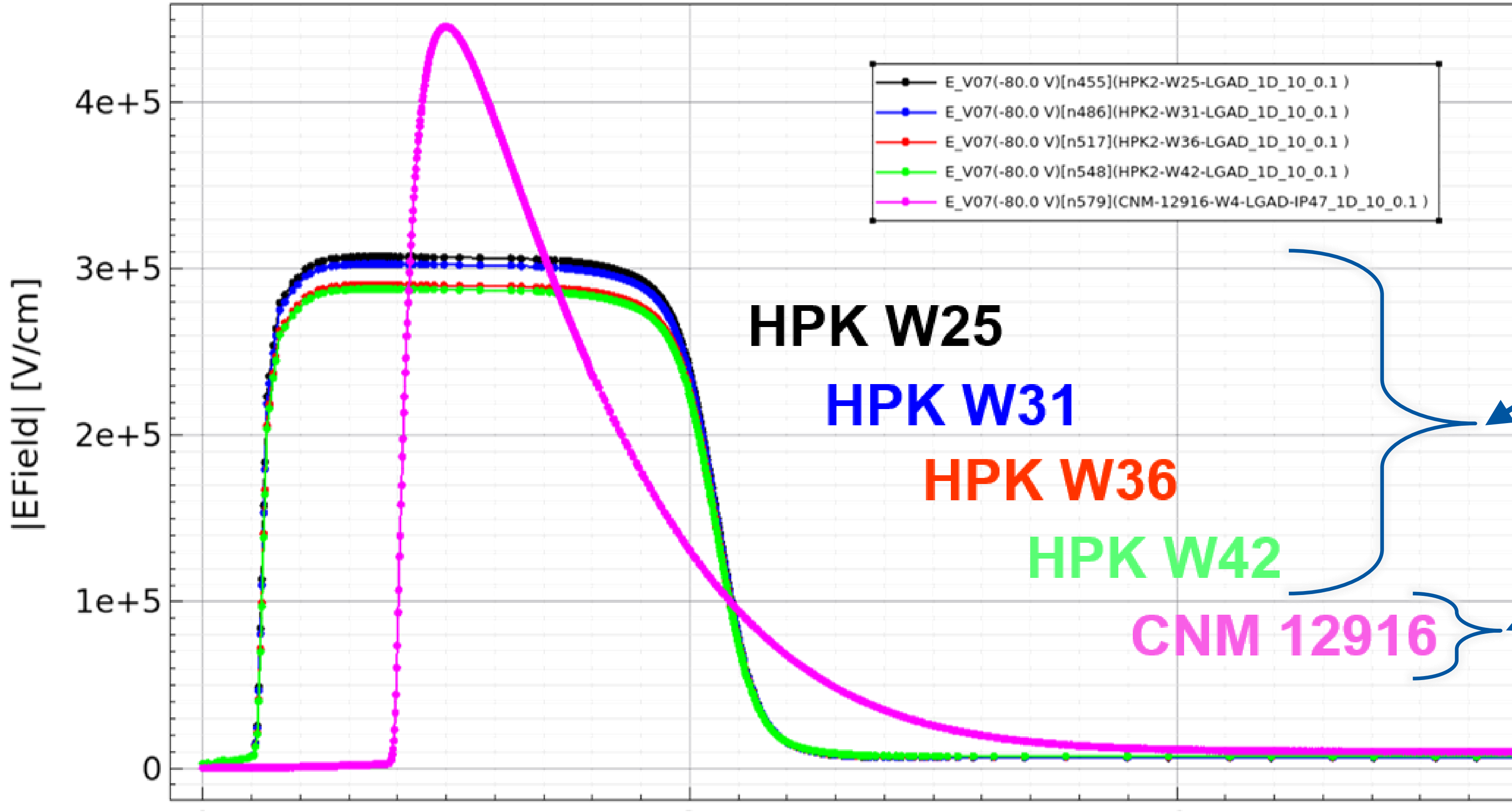


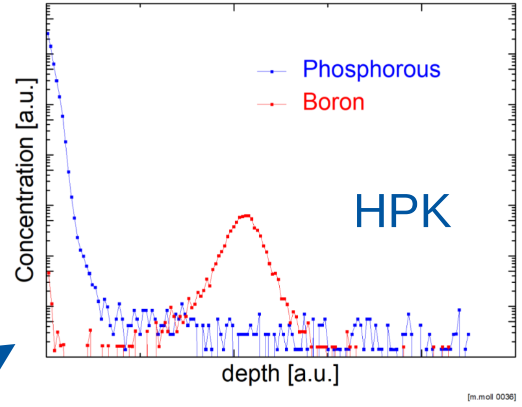
[M.Moll, 40th RD50 Workshop 06/2022 (link)]

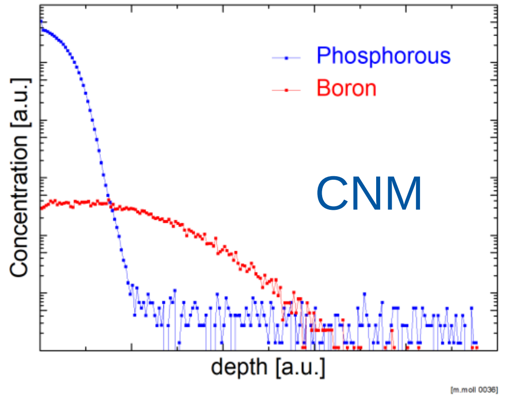
TCAD: Electric Field simulation

- Simulation of field at 80V



Doping profiles

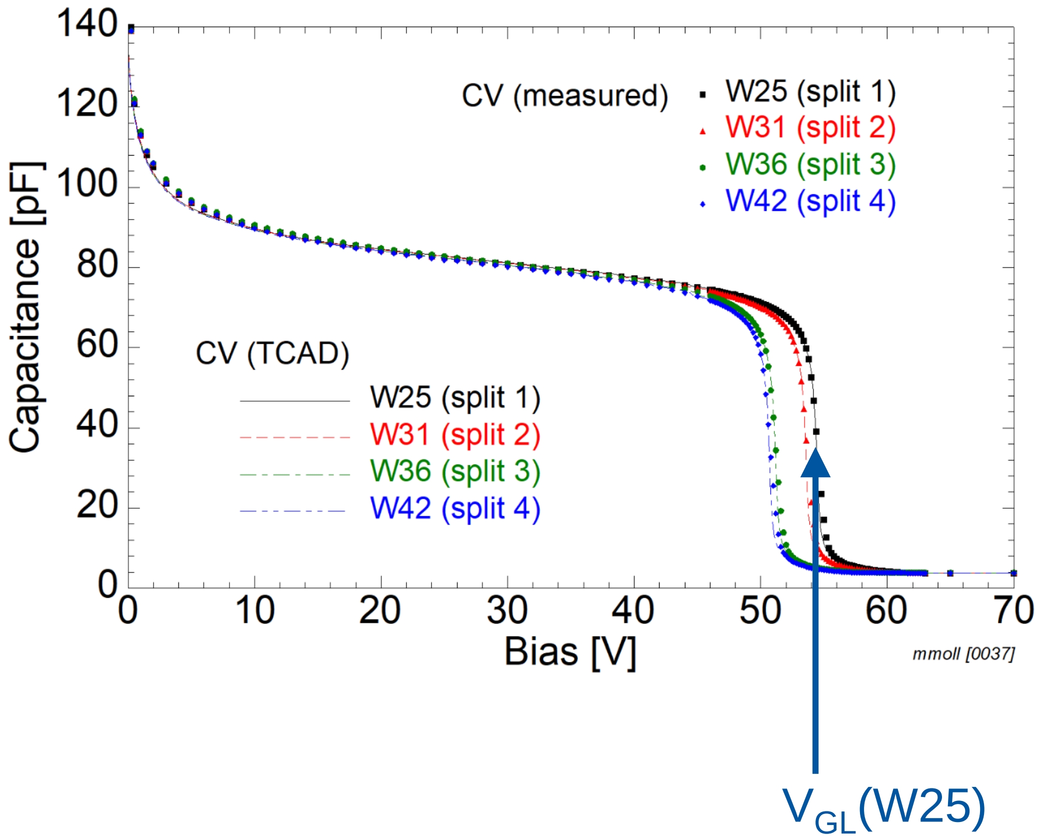


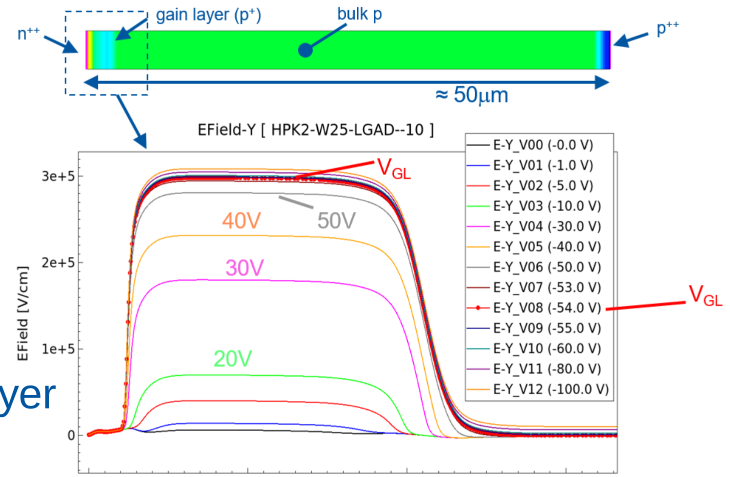


[M.Moll, 40th RD50 Workshop 06/2022 (link)]

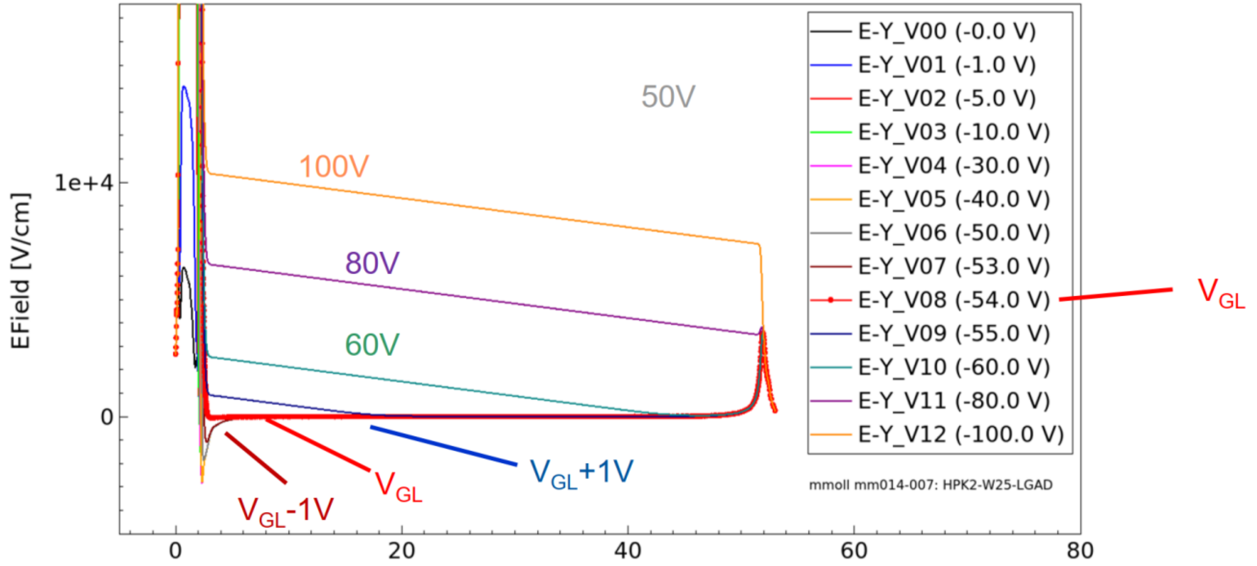
Gain layer depletion V_{GL}

- V_{GL}= "Gain Layer Depletion Voltage"
  - Voltage at which the electric field punches into the bulk.
  - Clearly visible in CV characteristics in the drop of capacitance
  - scales linear with integrated space charge N_{eff} in the gain layer (for a given doping profile)





Ramping up voltage:
(a) depletion of gain layer
(b) depletion of bulk

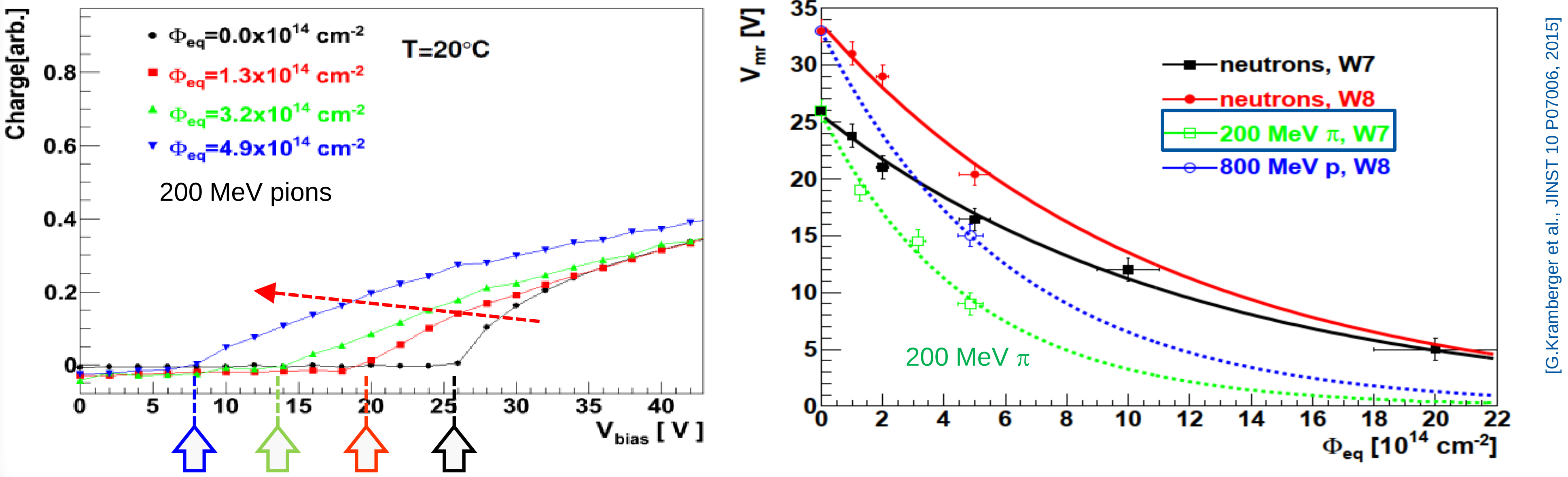


[M.Moll, 40th RD50 Workshop 06/2022 (link)]

Acceptor removal in LGAD gain layers

- Determination of (radiation induced) change in acceptor concentration (acceptor removal)
  - (I) Shift of the onset voltage V_{mr} for amplification (Analyze signal vs. voltage using TCT, beta CCE, test beam, ..)
  - (II) Shift of the characteristic capacitance drop in CV curves (Analyze the “foot” in the CV curve)
    - Assumption: The determined voltage is a clear measure for N_{eff} (i.e. [B]) within the gain layer

Method II: Signal (example: TCT; red front)



[G.Kramberger et al., JINST 10 P07006, 2015]

- Analyses for acceptor removal:

$$V_{mr} \approx V_{mr,0} \times \exp(-c\Phi_{eq}) \quad \Rightarrow \quad N_A \approx N_{A,0} \times \exp(-c\Phi_{eq})$$

- **Points of attention:** gain layer has a profile, not a constant doping; E-field in the sensor bulk can influence measurement

LGAD: Gain layer engineering

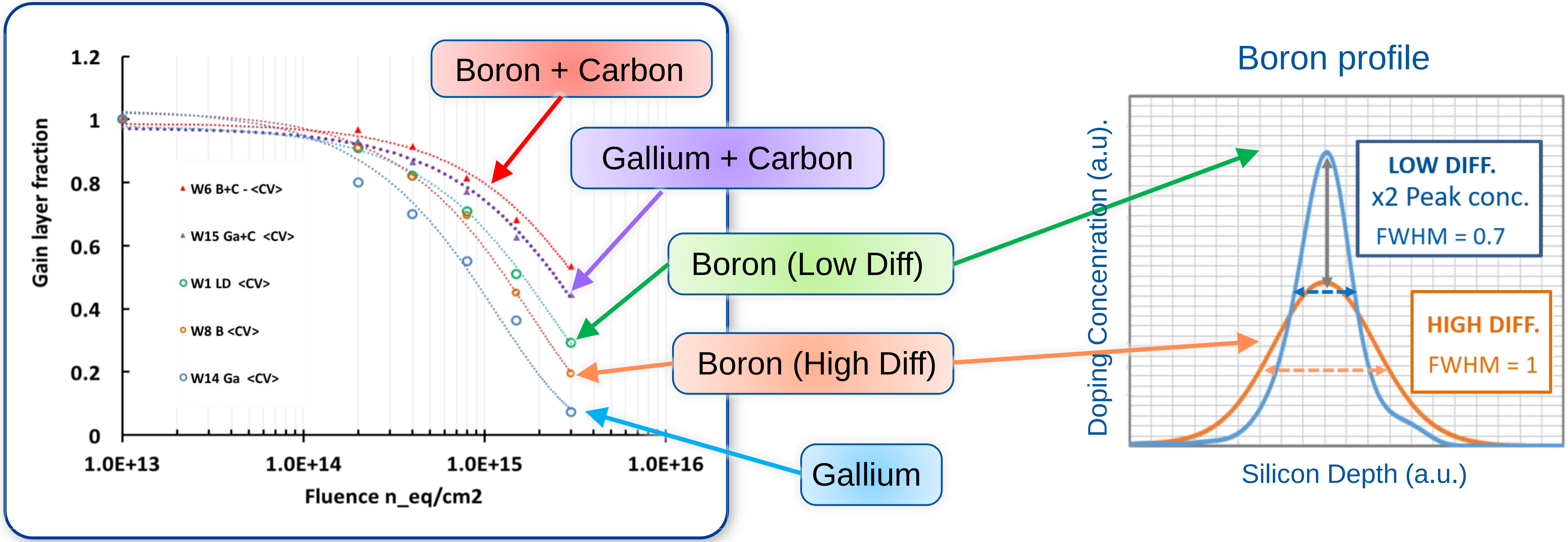
2020

Defect Engineering of the gain layer

- **Carbon** co-implantation mitigates the gain loss after irradiation
- Replacing Boron by **Gallium** did not improve the radiation hardness

Modification of the gain layer profile and implantation depth

- Narrower **Boron doping profiles** with high concentration peak (Low Thermal Diffusion) are less prone to be inactivated



[G.Paternoster, FBK, Trento, Feb.2019]

LGAD: Gain layer engineering

Defect Engineering of the gain layer

- **Carbon** co-implantation mitigates the gain loss after irradiation -> The mitigation effect depends on the Carbon dose.
- Replacing Boron by **Gallium** did not improve the radiation hardness

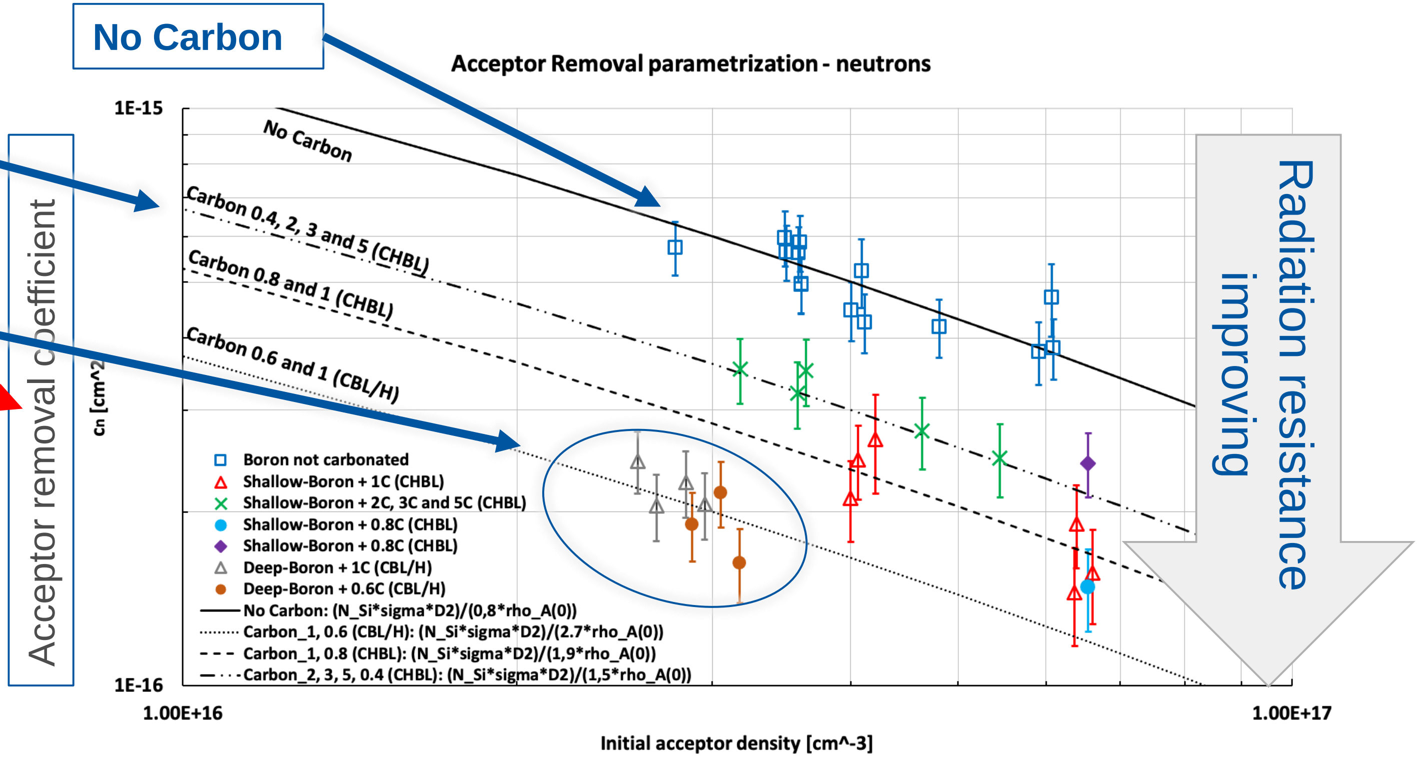
Modification of the gain layer profile

- Narrower **Boron doping profiles** with high concentration peak (Low Thermal Diffusion) are less prone to be inactivated

Too high or too low Carbon dose

Optimal carbon dose
with low thermal diffusion

$$V_{GL}(\Phi) \propto N_B(\Phi) = \mathrm{N}_{\mathrm{B}0}\exp(-c_A\Phi)$$

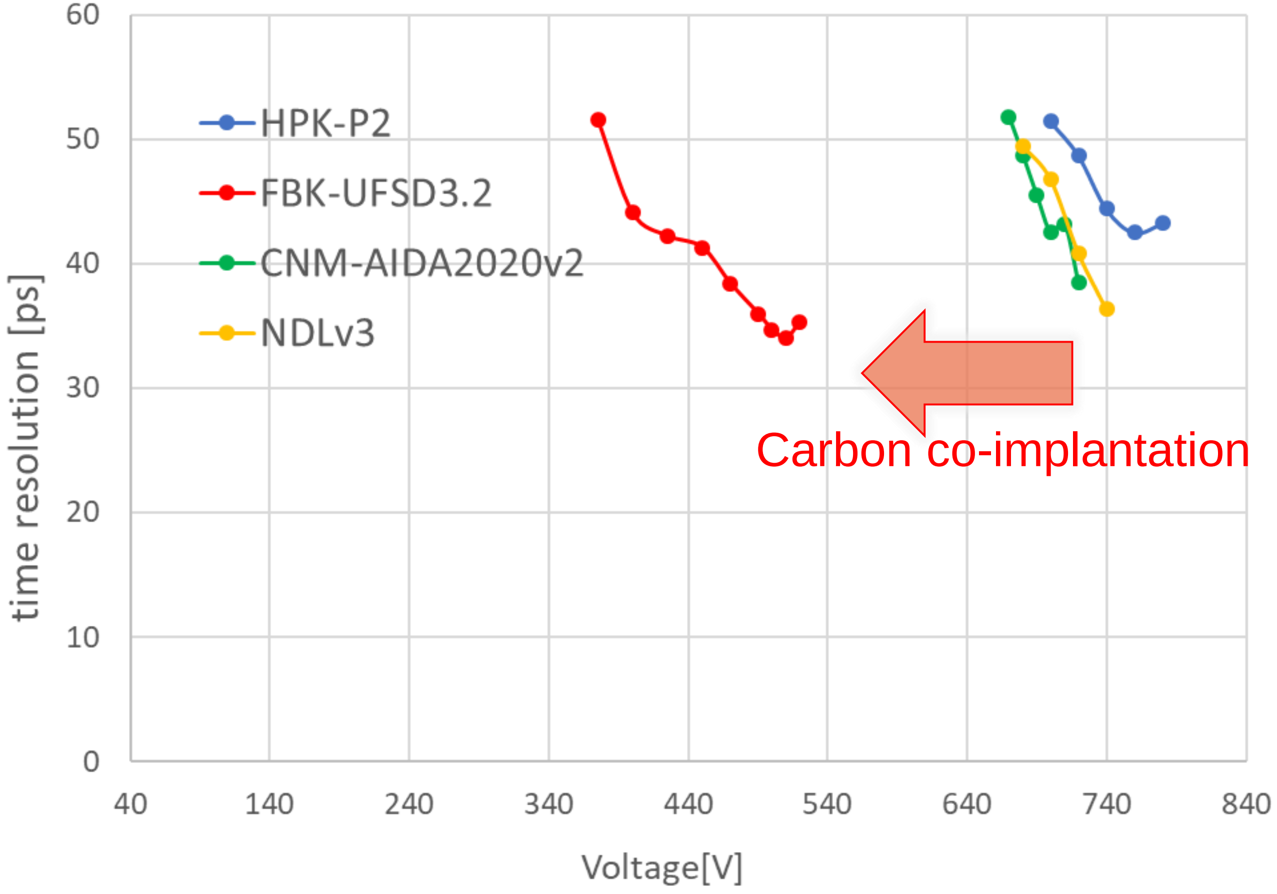


[M. Ferero, INFN To, 37th RD50 Workshop]

LGAD: Time resolution after irradiation

- Carbon co-implantation allows to reach an exceptional time resolution (~ 30 ps) after irradiation (2.5e15 $n_{eq}cm^{-2}$) using about 300 Volts less wrt not carbonated samples.

2.5e15 n_{eq} cm^{-2}



[A. Howard, 37th RD50 Workshop]

Defect spectroscopy on irradiated p-type sensors

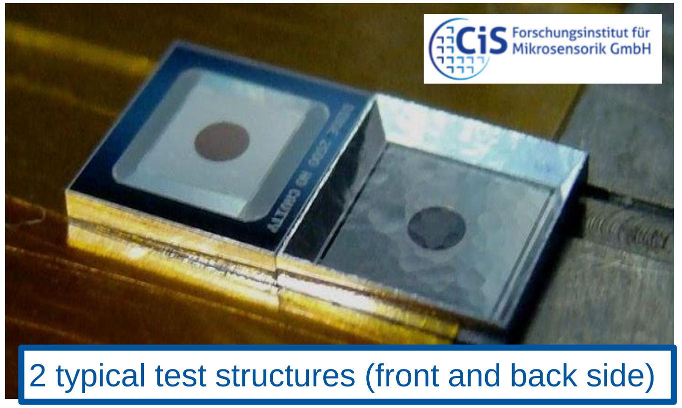
- DLTS
- TSC

Dedicated acceptor removal (defect) studies

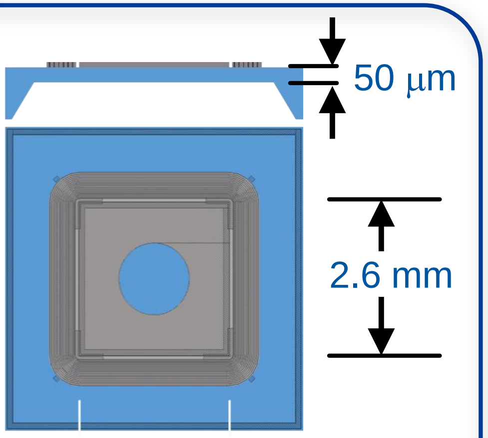
production & irradiation of test structures from various p-type silicon materials

RD50 project I : Results given in this presentation

- Material [boron doped]
  - **Epi Silicon (50 μm on Cz) 10, 50, 250 and 1000 Ωcm**
  - FZ Silicon (100 – 285 μm)
  - Cz/MCz Silicon (50-200 μm)
- Samples
  - p-n diodes (CiS & Minsk)
    - Metal opening for light injection
    - Thinned for TSC and TCT
- Characterization
  - CV, IV, TCT
  - TSC, DLTS, PL
- Irradiations
  - Protons (23 GeV; 230 MeV)
  - Neutrons (reactor)
  - Electrons (6 MeV; 200 MeV)
  - Gammas (^{60}Co)
  - Alphas (5.15 MeV)



2 typical test structures (front and back side)



Proton irradiation

24 GeV /c

Boston General Hospital

230 MeV

Neutron irradiation

Institut "Jožef Stefan"

Reactor neutrons

Gamma - irradiation

^{60}Co

50 kGy, 200 kGy and 1 MGy

Electron irradiation

+CLEAR

3.5 MeV, 5.5 MeV, 200 MeV

EP-DT-DD
Detector Technologies
Detector Development

RD50 Workshop presentations 06/2022: A.Himmerlich [link], C.Liao [link], I.Pintilie [link], K.Lauer [link]

RD50 project II (2019-03)

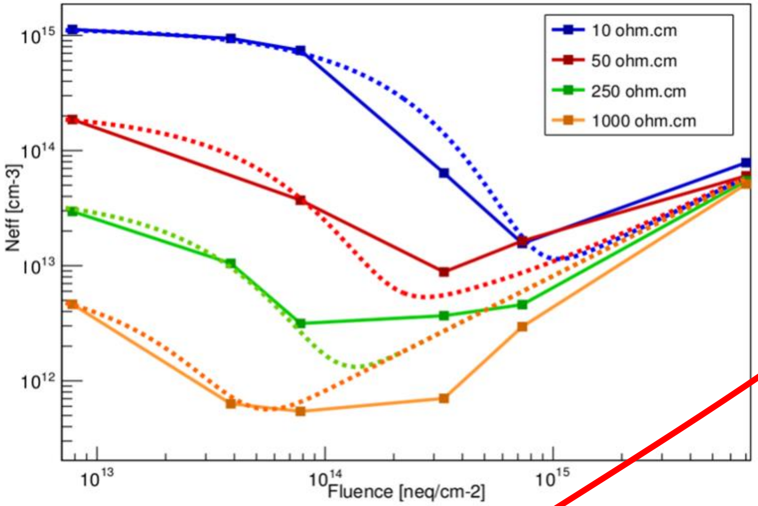
- Extension of doping range
- Inclusion of Schottky diodes
- Large amount of samples
- Material [boron doped]
  - **Epi Silicon (50 μm on Cz) 0.2, 1.5, 15, 150 and 1500 Ωcm**
  - 125 wafers ([B] = 10^{13} to 10^{17} cm^{-3})
- Samples
  - p-n diodes (CUMFF, Canada)
  - Schottky diodes (RAL, UK)
    - Metal opening for light injection
- Characterization
  - CV, IV
  - DLTS, TAS, TCAD
  - first results on non-irradiated samples
- Irradiations
  - in progress

RD50 Workshop 06/2022: C.Klein [link], C.Liao [link]

RD50: Dedicated acceptor removal studies

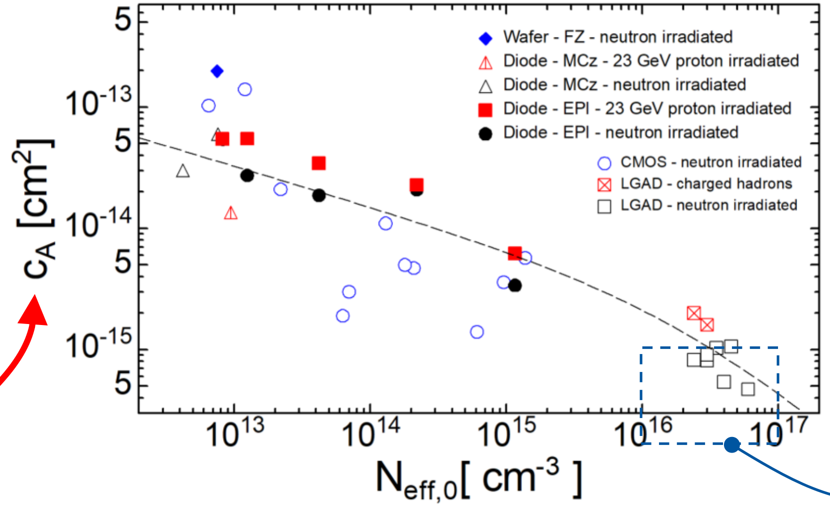
- **Acceptor removal:** Radiation induced de-activation of acceptors (p-type doping, Boron)
- Impact:
  - Change of silicon conductivity; Change of sensor depletion voltage and/or active volume
  - **Loss of gain in LGAD sensors,** sets radiation hardness limits for timing detectors (ETL, HGTD)
- Macroscopic studies:

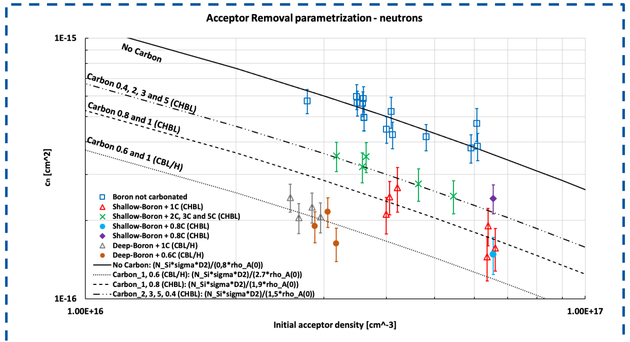
Example: 23 GeV proton irradiated epi diodes



[M.Moll – PoS(Vertex2019)027]

$$N_{eff}(\Phi) = N_{B0}\exp(-c_A\Phi) + g\cdot\Phi$$





..see previous slide
on C-enriched LGAD

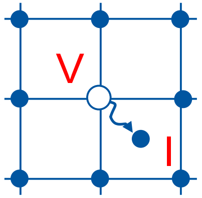
- Acceptor removal coefficients obtained on a wide range of sensor types
  - pin diodes (epi, FZ, MCZ, …), LGAD detectors, CMOS sensors
  - after charged hadron irradiation (red) and neutron irradiation (black/blue)

- **Parameterization of acceptor removal established within RD50**
  - covering the range [B]=10^{12} to 10^{18} cm^{-3} (10 kΩcm to 5 mΩcm) i.e. damage predictions can be done

Displacement Damage

particle → *Si_S*

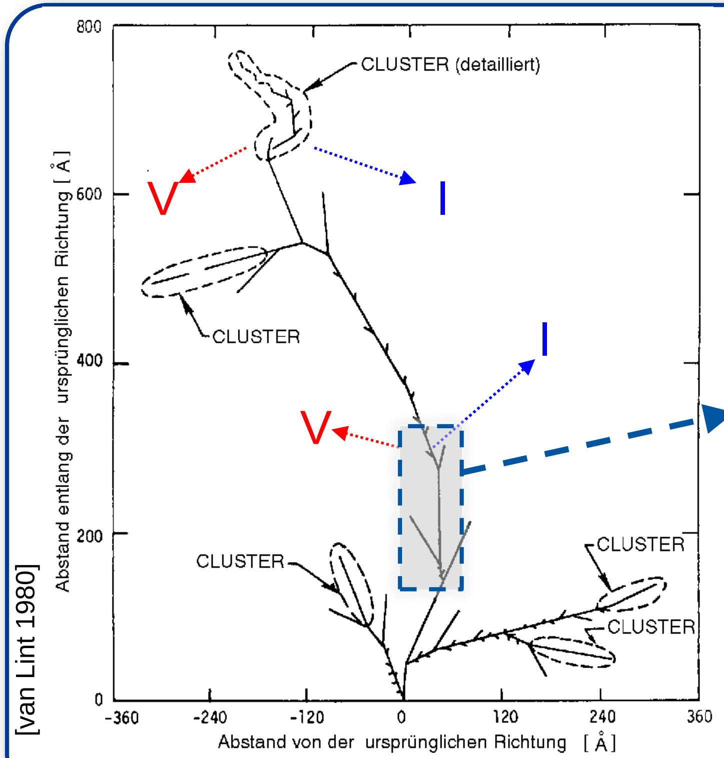
E_K>25 eV →



Vacancy
+
Interstitial

→ ..... *a wide range of* ***point defects***

E_K>5 keV → *point defects and clusters of defects*

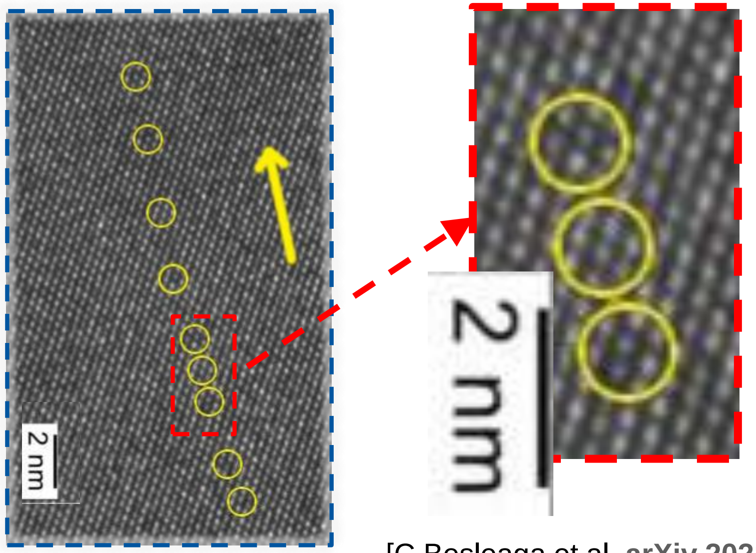


[van Lint 1980]

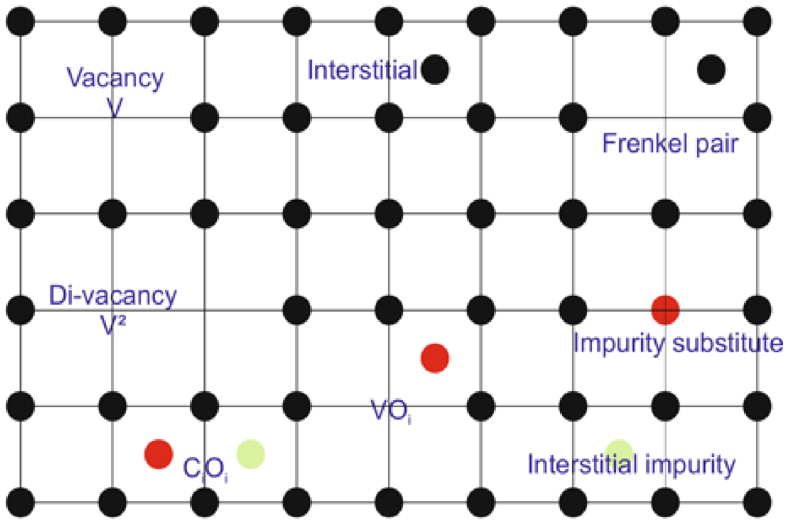
Can we see the defects?

HRTEM on Si: n-irradiated 10^{19} n_{eq}/cm^2

High Resolution Transmission Electron Microscopy



[C.Besleaga et al. arXiv 2021]



- example of point defect reactions:

V: $V+O \rightarrow VO$; $V+P \rightarrow VP$ ← "dopant removal"

I: $I+C_S \rightarrow C_i \rightarrow C_i + O \rightarrow C_iO_i$

$I+B_S \rightarrow B_i \rightarrow B_i + O \rightarrow B_iO_i$

... many more reactions!

TSC: Thermally Stimulated Current

- Measurement cycle
  (1) Cooling
  - under bias or without

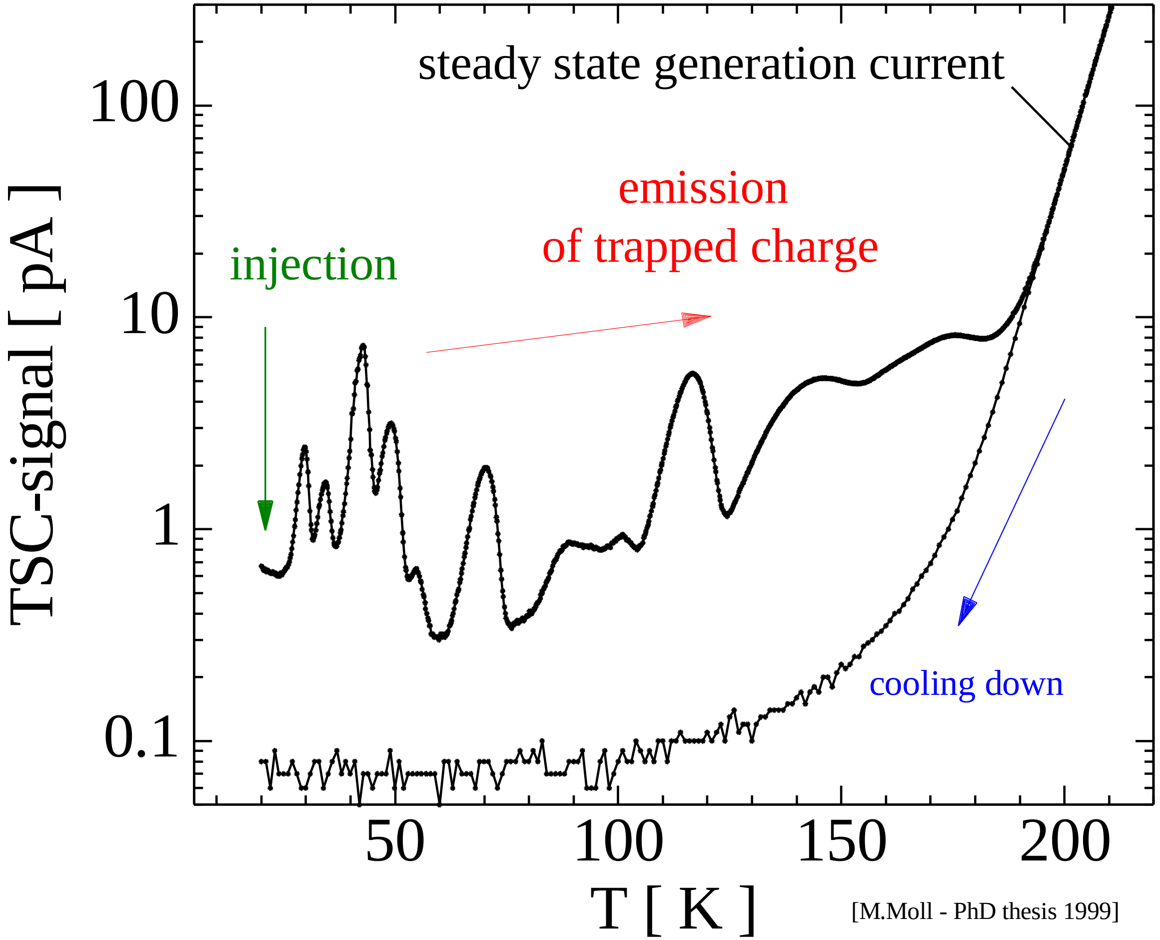
  (2) Filling (charge injection)
  - Forward bias, zero bias, optical filling

  (3) Current measurement
  - Measure current while ramping up the temperature, discharging of traps results in current peaks

- Analyses
  - **Peak heights** or integral over peak
    - → Defect concentration
  - **Peak position** gives indication for E_a and cross section σ
    - more precise: fit to spectrum and/or delayed heating measurement (see next slide)

Current

$$I_{TSC}(T) = \frac{1}{2}\, q_0 A w(T) N_t \cdot e_n(T) \cdot exp\left(-\frac{1}{\beta}\int_{T_0}^{T} e_n(T)dT\right)$$



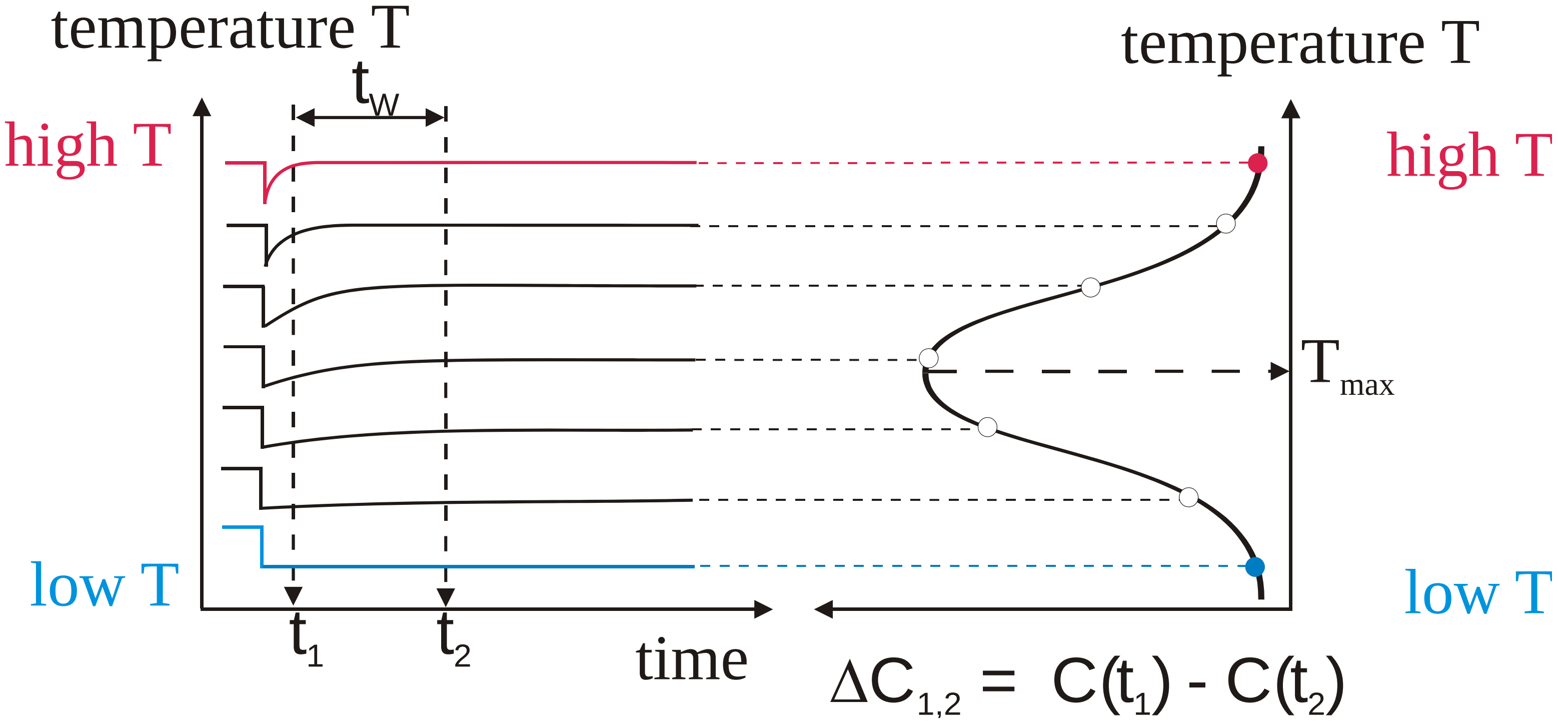
[M.Moll - PhD thesis 1999]

Note: hole and electron traps give same polarity signal

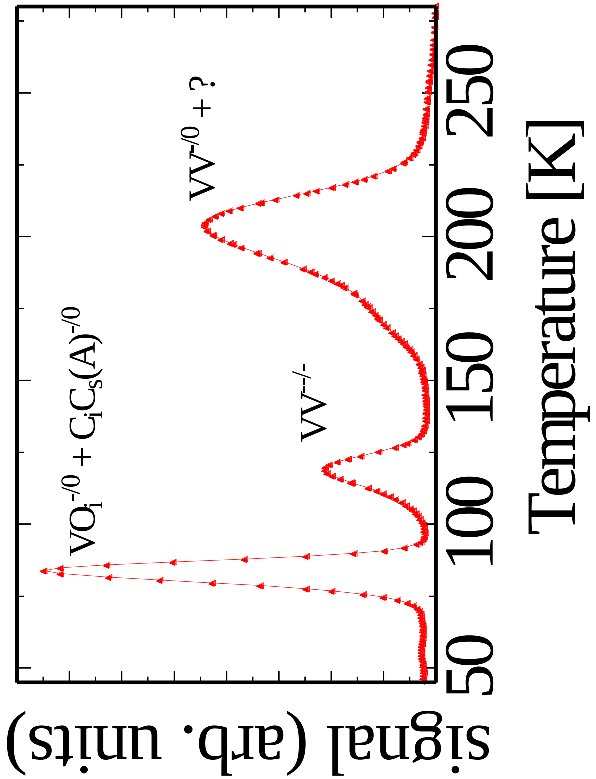
[M.Moll – Characterization of radiation induced defects in silicon devices – June 2021, Lyon]

DLTS (Deep Level Transient Spectroscopy): Spectrum

- **DLTS spectrum** is obtained from (Capacitance) transients measured at different temperatures



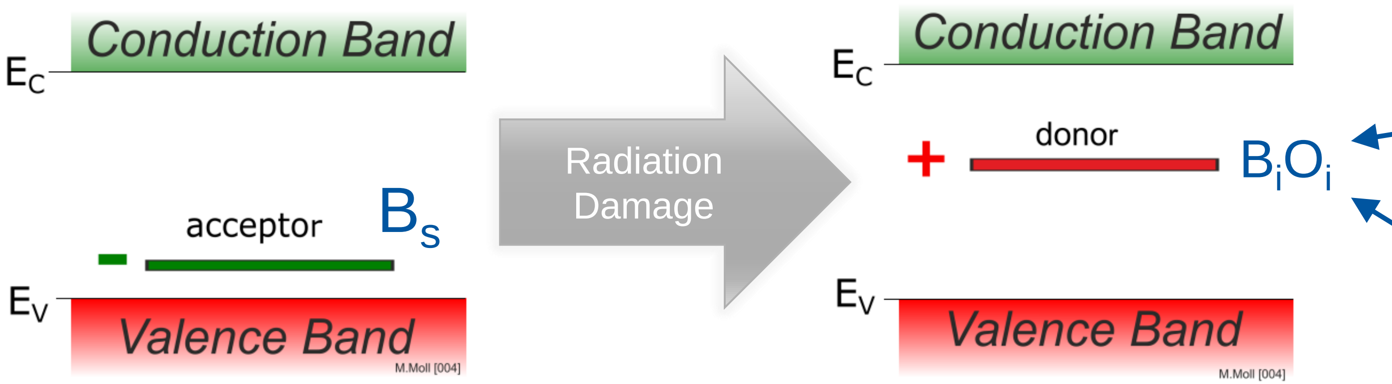
$$\Delta C_{1,2} = C(t_1) - C(t_2)$$

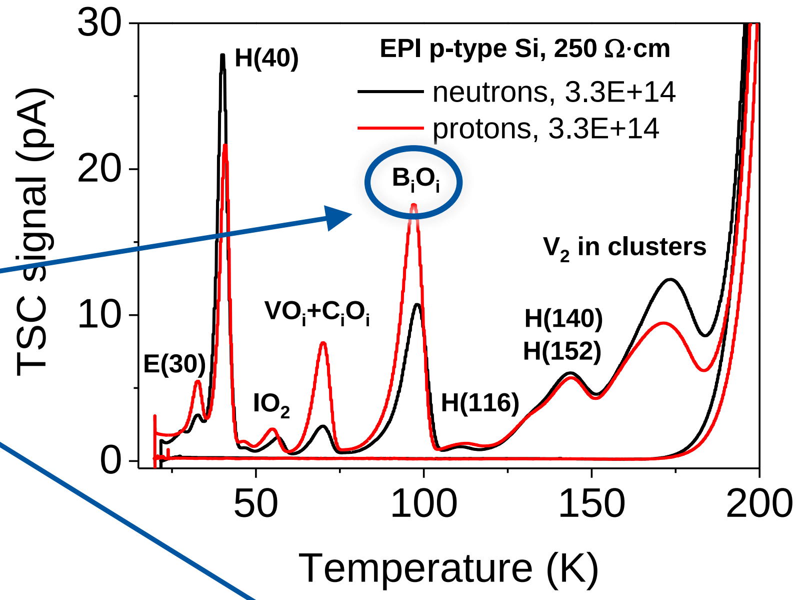


[M.Moll – Characterization of radiation induced defects in silicon devices – June 2021, Lyon]

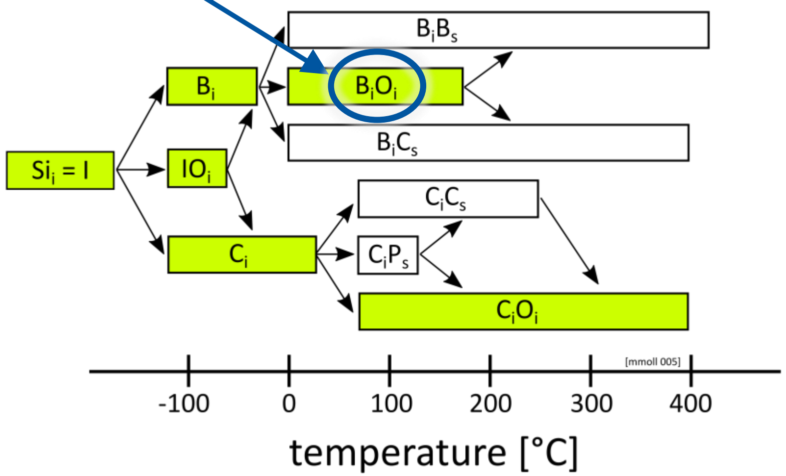
Defect studies: Acceptor Removal

- Microscopic origin:
  - Formation of defects containing Boron that no longer acts as shallow dopant



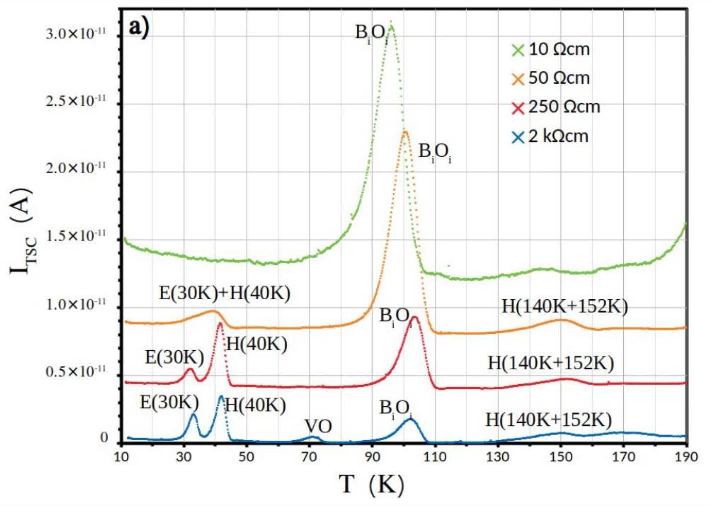


- Status
  - Large amount of data (Wafers, Detectors, CMOS, LGAD)
  - Acceptor removal is parametrized over 6 orders of magnitude in resistivity
    - Damage predictions are possible
  - Defect engineering (with Carbon) works
    but microscopic understanding needs more work!
    - Measured defect concentrations do not fully explain the macroscopic observations.

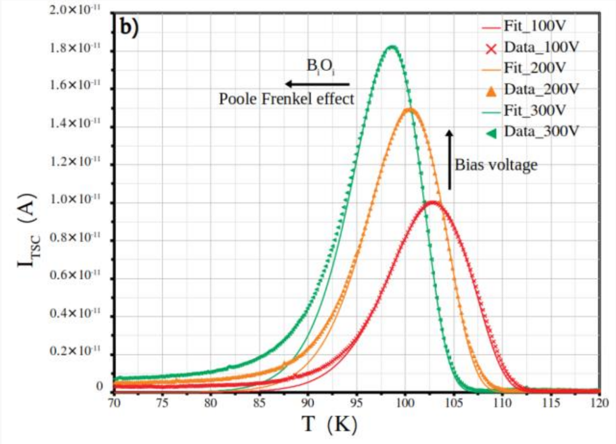


Characterization of the B_iO_i defect

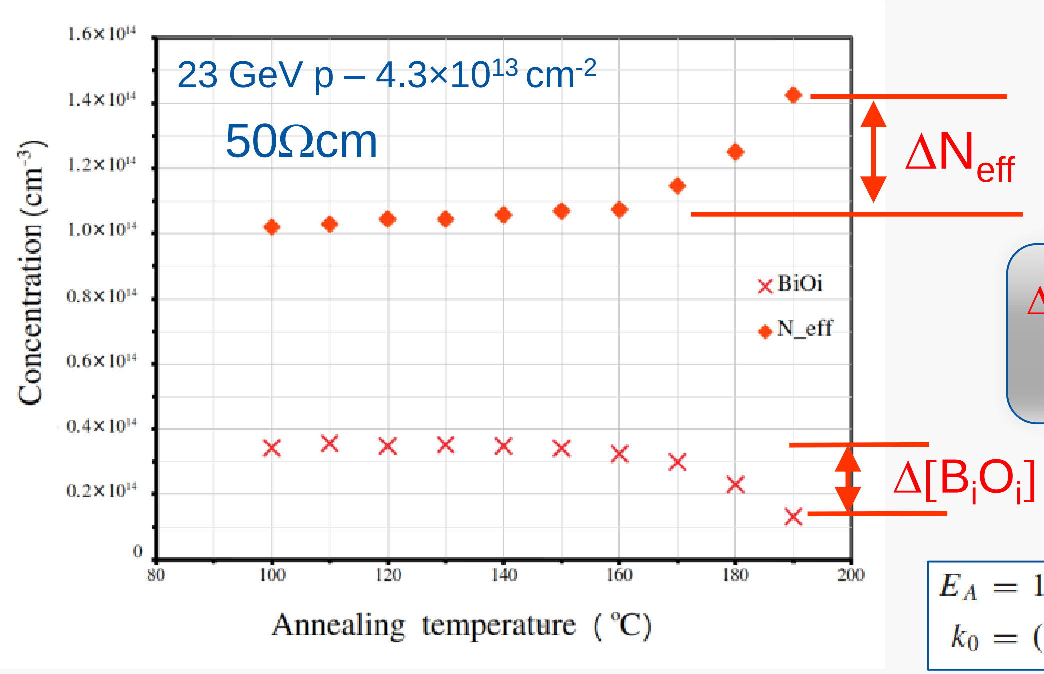
..detected in all p-type samples



..strong Poole Frenkel effect → donor



....isochronal annealing: N_{eff} & [BiOi] (i.e. CV and TSC)



$\Delta N_{eff} \approx 2 \times \Delta[B_iO_i]$

$B_iO_i(+) \rightarrow B_s(-)$

$$E_A = 1.35 \pm 0.01 \; [\mathrm{eV}]$$
$$k_0 = (2.58 \pm 0.5) \times 10^{11} \; [\mathrm{s}^{-1}]$$

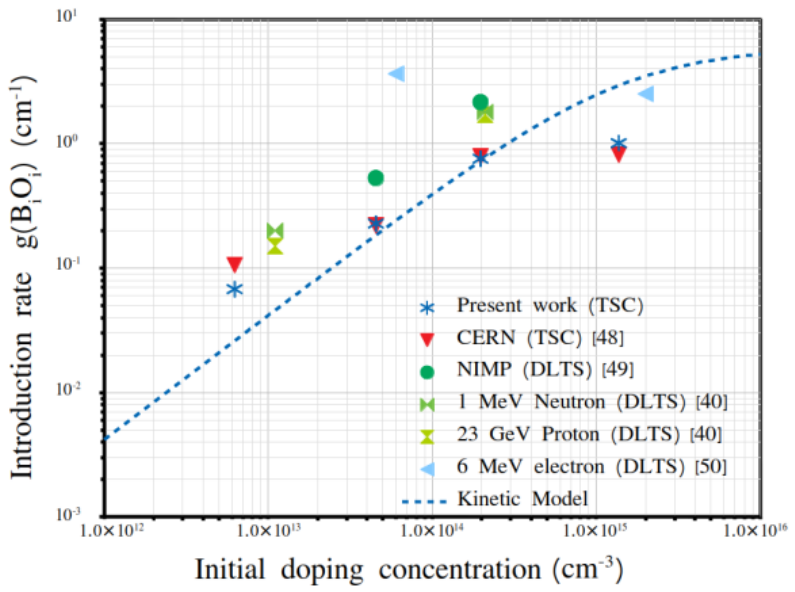
Observation: level at ≈ E_C-0.25 eV, related to boron, electron trap, strong Poole Frenkel effect hinting to donor level, annealing at ≈180°C gives negative space charge

→ level is matching an assignment as $B_iO_i^{(0/+)}$

[C.Liao et al. The Boron–Oxygen (BiOi) Defect Complex,2022, IEEE TNS (DOI)]
[I.Pintilie et al., Bistability of the BiOi complex and implecation on evaluation of acceptor removal, NIMA, 2021 (DOI)]

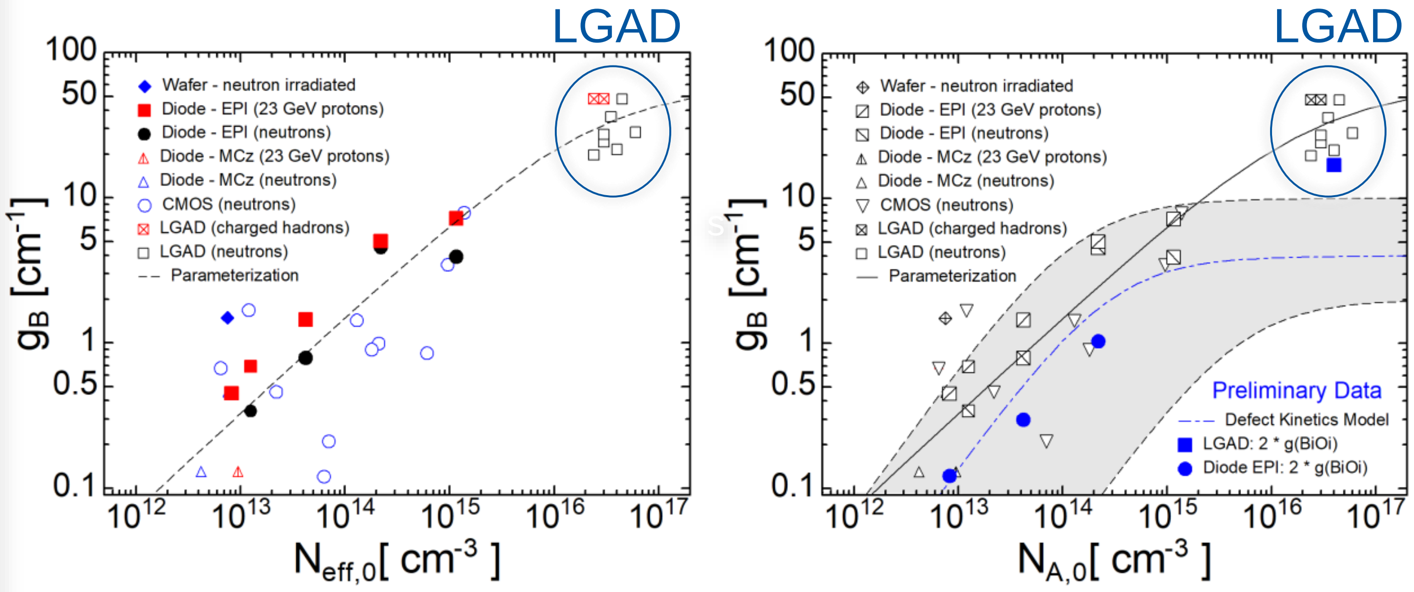
Can we explain the acceptor removal effect in LGADs?

- Low [B] (up to some 10^{14}cm^{-3} ≈ 10Ωcm)
  - Defect kinetics in terms of BiOi formation as function of boron concentration in reasonable agreement with (simple) kinetic models.



[C.Liao et al. The Boron–Oxygen (BiOi) Defect Complex,2022, IEEE TNS (DOI)]

- High [B] (10^{17}cm^{-3} ≈ LGAD gain layers)
  - Extrapolation of simple defect kinetics model does not work: Further work needed to fully explain acceptor removal effect!



[M.Moll,Acceptor removal, 2020, Proceedings of Science (DOI)]

- Strong fluctuation of data on acceptor removal parameters and BiOi generation indicating a multi-stable defect?

[I.Pintilie et al., Bistability of the BiOi complex, implication on evaluation of acceptor removal, NIMA, 2021 (DOI)]

- Are boron clusters (B_nI_m) playing a role that could explain the high removal rates in the gain layer?

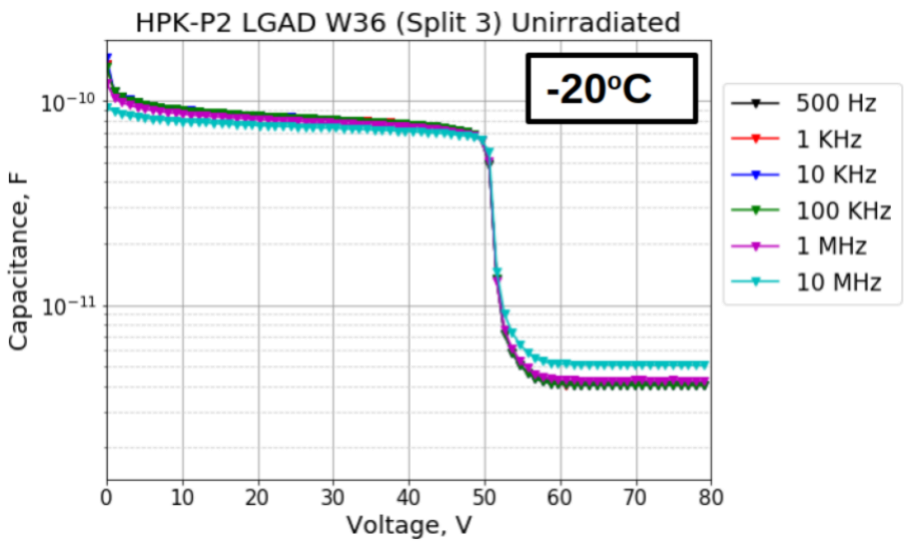
[P.Lopez et al, Atomistic simulation of acceptor removal, NIMB 2022 (DOI)]

Defect spectroscopy on irradiated LGADs

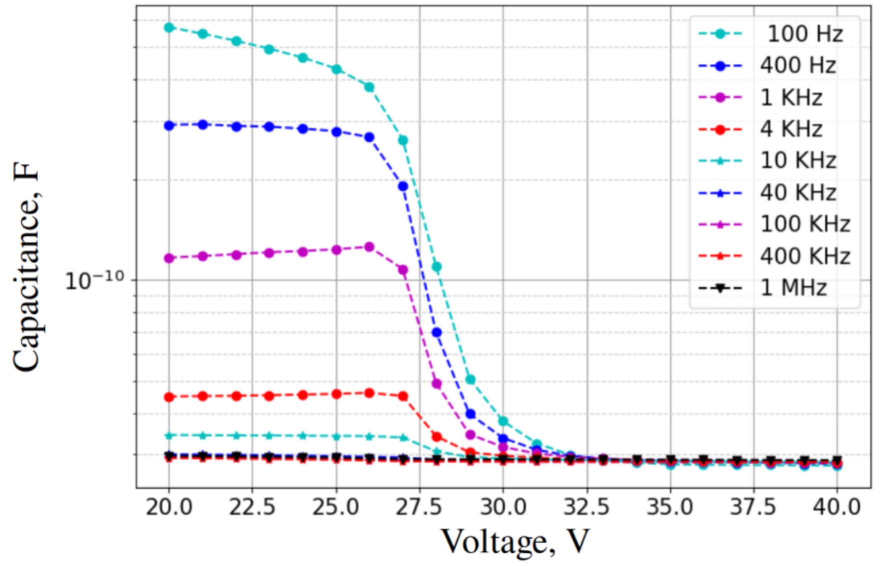
- DLTS
- TSC

C-DLTS on irradiated LGADs

- LGADs (= Gain layer + bulk) have a very inhomogeneous doping profile
  - Capacitance based DLTS studies not possible *(or at least very challenging)*



neutron irradiation
10^{14} n_{eq}/cm^2



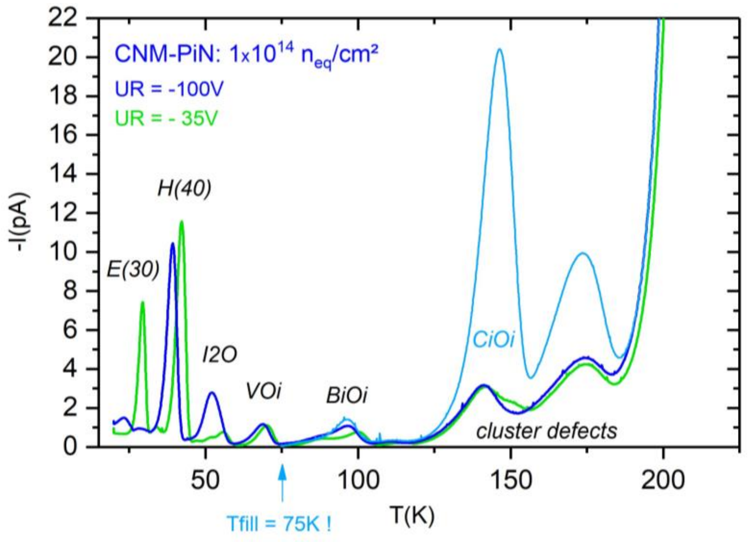
- After radiation levels that would allow to detect defects in silicon corresponding to the doping level of the gain layer, the bulk is already too strongly damaged to allow for DLTS measurements on the LGAD.

- A.Himmerlich, Defect spectroscopy studies on irradiated LGADs, Trento Workshop 03/2022 (link)
- A.Himmerlich, Defect characterization studies on neutron irradiated boron-doped pad/LGAD (submitted for publication in NIMA)

TSC on irradiated LGADs

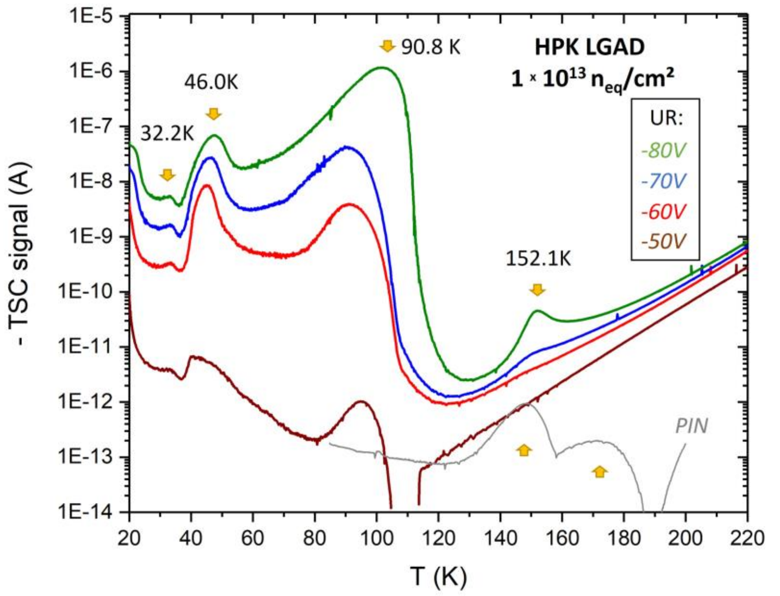
- TSC – Thermally Stimulated Currents
  - is applicable but obtaining reliable defect concentrations is very challenging

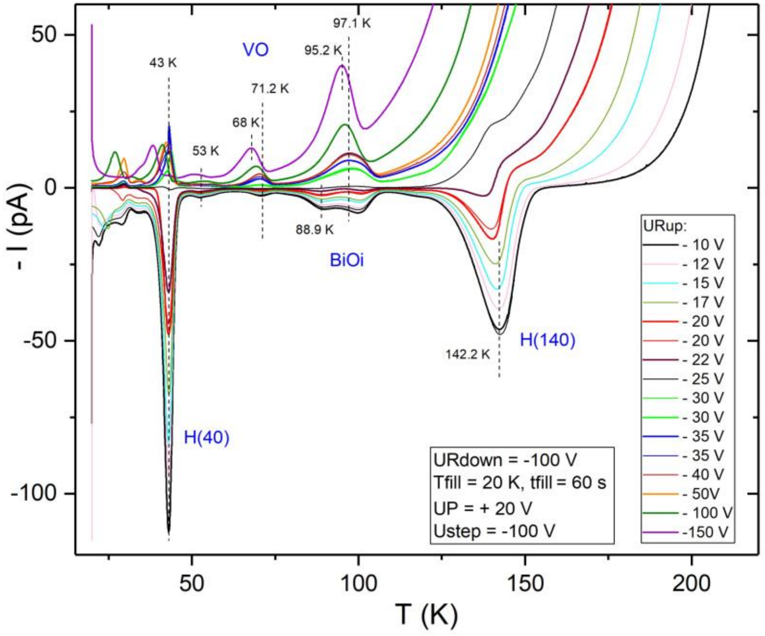
high resistivity pin diode



- A.Himmerlich, Defect spectroscopy studies on irradiated LGADs, Trento Workshop 03/2022 (link)
- A.Himmerlich, Defect characterization studies on neutron irradiated boron-doped pad/LGAD (submitted for publication in NIMA)

LGAD sensors (HPK/CNM)





- inhomogeneous signal amplification due to gain layer
- polarisation fields observed (that even can invert the current)

Outlook:

Dedicated test structures for defect spectroscopy

- **RD50 common project on dedicated test structures**
  - Produce test structures for defect spectroscopy that are mimicking the gain layer of LGADs
    - i.e. a sensor consisting only of gain layer like bulk material
  - Different levels of boron doping (close to the gain layer doping)
  - Different levels of carbon co-implantation
  - Project to start in 2023
    - Status: Approved by RD50 for co-funding
  - …open for collaboration ☺

Title of the project: *Defect engineering in PAD diodes mimicking the gain layer in LGADs*

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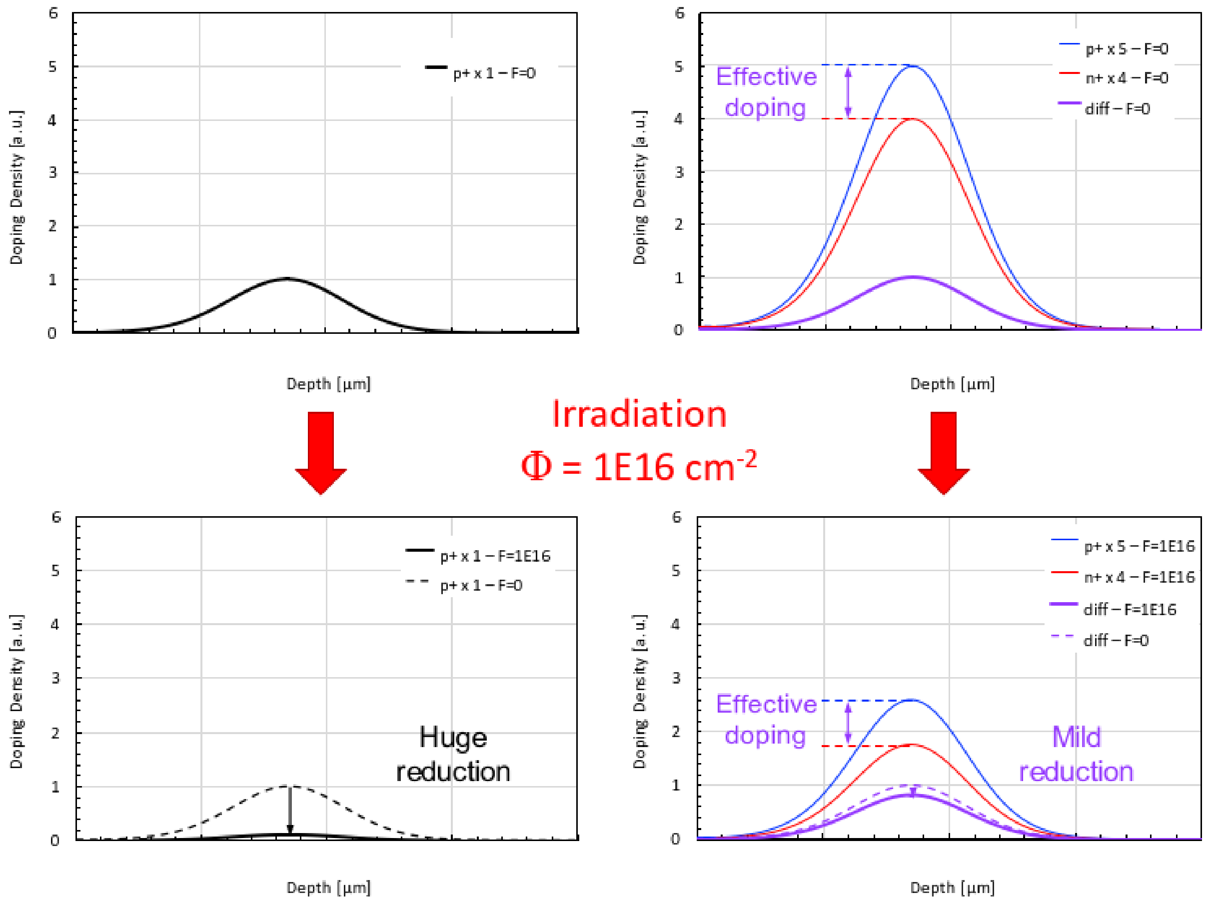
Outlook: Compensated gain layers

- Idea: Compensated gain layers
  - Produce a compensated gain layer (e.g. Boron + Phosphorus doped), so that the concentration of the dopants is higher while the space charge (i.e. the amplifying field) remains the same
    - Boron and Phosphorus are both 'removed' under irradiation
    - If in the removal process the difference between the dopant concentrations remains constant, radiation hardness is gained.
  - Does a compensated gain layer provide a higher radiation hardness?
    - ..project started as AIDAinnova Blue Sky Project



Standard LGAD design

Compensated LGAD design

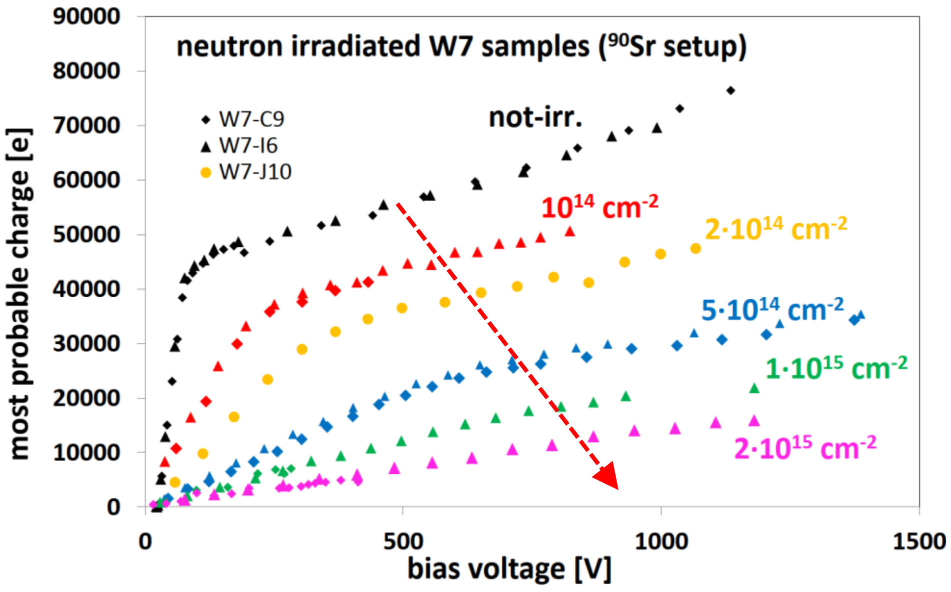
[V.Sola et al, Thin Silicon Sensors for Extreme Fluences, AIDAinnova Blue Sky Project, March 2022 (link)]

Conclusions

- Radiation induced acceptor removal effect leads to performance changes (mostly degradation) in LGAD, CMOS and standard p-type detectors.
  - It is the limiting factor for LGAD sensor application in high radiation fields!
- **Parameterization of acceptor removal existing** and covering the range $[B]=10^{12}$ to 10^{18} cm^{-3} (10 kΩcm to 5 mΩcm)
  - i.e. damage prediction can be done
- **Gain layer engineering: Carbon enrichment reduces "removal speed"**
  - LGAD sensors can gain a factor of order 2-3 in fluence reach by gain layer engineering
- **Microscopic understanding remains incomplete (my opinion)**
  - Measured defect concentrations (so far) do not explain the observed acceptor removal effect
  - Two modelling approaches presented (both lacking some consistency with data)
    - Model I (Torino): Good parameterization to all experimental data measured on macroscopic scale. Can be used for damage predictions. Difficult to include in the microscopic picture as we need an invisible sink for interstitials ("dark interstitial sink")
    - Model II (Defect formation): We can explain the BiOi formation in high resistivity materials up to 10 Ωcm but not beyond (i.e. the strong BiOi formation in LGAD sensors).
    - Model III (Kinetic Monte Carlo modelling with boron clusters) offer a new approach (under study)
- **Need more data/models: Dedicated RD50 projects started and ongoing**

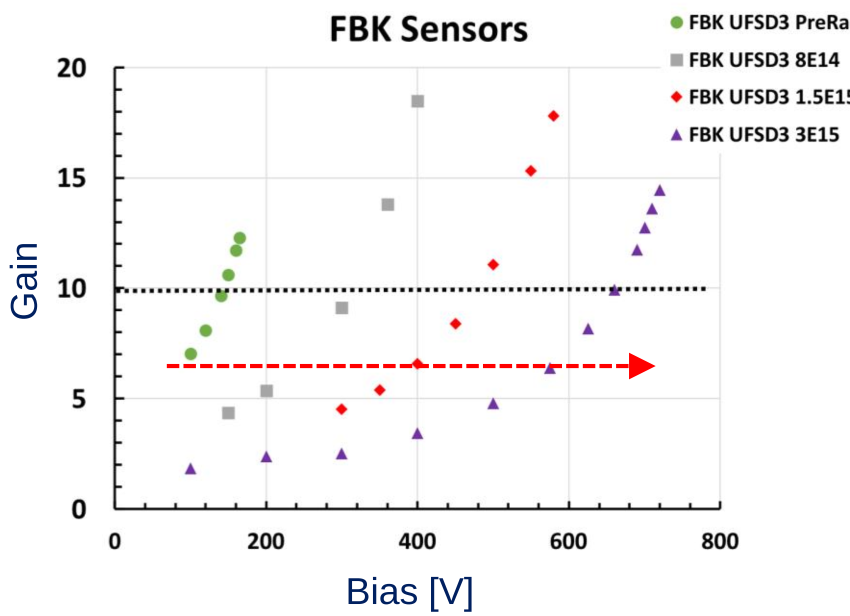
Radiation damage to LGADs

- Decrease of signal gain with increasing particle fluence
  - Main reason: Radiation induced degradation of the gain layer
  - Gain layer is (usually) a Boron implant that is suffering from “acceptor removal”
  - Mitigation: Increase of voltage to enhance the impact ionization



[G.Kramberger et al., JINST 10 P07006, 2015]

Loss of signal gain with increasing fluence for fixed voltage



[CMS TDR of the MTD, 2019]

Increasing voltage needed to reach a gain of 10